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Mr. Chairman, Ranking Minority Member, and members of the committee: thank you for inviting me here to testify today. My name is Louis Lanzerotti and I am a professor of Physics at the New Jersey Institute of Technology and a consultant for Bell Laboratories, Lucent Technologies. I appear today in my capacity as chair of the National Research Council (NRC)'s Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope.

As you know the NRC is the unit of the National Academies that is responsible for organizing independent advisory studies for the federal government on science and technology. In early 2004 the NRC was asked by Congress and NASA to examine the issues surrounding the cancellation of the final servicing mission (SM4) for the Hubble Space Telescope and to consider both the value of preserving Hubble and the potential methods for doing so. Specifically called out in the tasking was a requirement to survey the potentials of both on-orbit and robotic intervention. The National Research Council formed a committee under the auspices of the Space Studies Board and the Aeronautics and Space Engineering Board to respond to this request.

After detailed examination of the astronomical evidence that was presented to it, the committee concluded that NASA should commit to a Hubble serving mission that accomplishes the objectives of the originally planned SM-4 mission. This includes the emplacement of two new instruments, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera-3 (WFC3), as well as refurbishments of those spacecraft subsystems that are required to preserve the health and safety of the telescope, both for science as well as for eventual safe de-orbiting.

The committee's principle conclusions related to the mission risk of servicing Hubble were:

> *The need for timely servicing of Hubble, due to lifetime limits on various engineering subsystems, imposes difficult requirements on the development of a robotic servicing mission. The very aggressive schedule, the complexity of the over-all mission system design (which is in a rudimentary state), the current low level of technology maturity (other than the yet-to-be flown International Space Station (ISS) Special Purpose Dexterous Manipulator System (SPDM) and Grapple Arm (GA; essentially the Shuttle Remote Manipulator System (RMS)), and the inability of a robotics mission to respond to unforeseen failures that may well occur on Hubble between now and a robotic servicing mission make it highly unlikely that the science life of HST will be extended through robotic servicing.
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> *A shuttle servicing mission is the best option for extending the life of Hubble and preparing the observatory for eventual robotic de-orbit; such a mission is highly likely to succeed. The committee believes that this servicing mission could occur as early as the seventh shuttle mission following return to flight, at which point critical shuttle missions required for maintaining the ISS will have been accomplished.

It is obvious that a robotic servicing mission to Hubble would involve no risk to astronauts. However, the committee was informed that the nation is committed to 25 to 30 human shuttle flights to the International Space Station (ISS). In reviewing all of the data presented to it, and in making use of the expertise of the committee's members who have deep experience in human space flight as well as in managing the nation's human space flight program,

> *The committee concluded that the difference between the risk faced by the crew of a single shuttle mission to the ISS—already accepted by NASA and the nation—and the risk faced by the crew of a shuttle mission to HST is very small. Given the intrinsic value of a serviced Hubble, and the high likelihood of success for a shuttle servicing mission, the committee judges that such a mission is worth the risk.

As I noted, these conclusions were reached after a considerable, in-depth examination of technical data and documents, presentations by expert witnesses, extensive exchanges and consultations with NASA, industry and academic colleagues, and multiple site visits to the Goddard Space Flight Center and the Johnson Space Flight Center. The committee members have outstanding, world-recognized credentials in not only the diverse fields relevant to this study (ranging from risk assessment to astronomy) but also in their decades of direct, practical, experience with the NASA spacecraft systems and programs that were being evaluated. Two of my committee members, General Charles Bolden, a veteran former astronaut whose shuttle missions include the deployment of the Hubble Space Telescope, and Mr. Joseph Rothenberg, former Associate Administrator of Spaceflight at NASA and former director of the Goddard Space Flight Center, are present with me today and are available to answer questions.

Before I continue I would like to note, and indeed stress, that when this study was initiated, I found a broad diversity of opinion among the committee members on both the question of whether Hubble should be preserved, and if so, which method of doing so was preferable. After all, from my personal experience and the experience of some members of the committee, almost no space researcher is ever in favor of turning off an operating spacecraft that is continuing to return excellent data. Hence, some members of the committee questioned at the outset of our study the very premise of keeping Hubble alive. It was only after a vigorous and painstaking exploration of the information presented to us, and considerable questioning analysis, that the committee reached the conclusions that are found in our report. Those conclusions were reached unanimously, and without reservation, by our entire membership.

Of the many issues considered by the committee, I have been asked to focus today on 1) Hubble's contribution to science and what its loss or performance interruption would mean, and the 2) the comparative strengths and weaknesses of a shuttle servicing mission, a robotic servicing mission, and a rehosting mission. I will therefore devote the remainder of my testimony to these issues.

The Past and Future Contributions of Hubble

Over its lifetime, the HST has been an enormous scientific success, having earned extraordinary scientific and public recognition for its contributions to all areas of astronomy. Hubble is the most powerful space astronomical facility ever built, and it provides wavelength coverage and capabilities that are unmatched by any other optical telescope currently operating or planned. Much of Hubble's extraordinary impact was foreseen when the telescope was being planned. It was predicted, for example, that the space telescope would reveal massive black holes at the centers of nearby galaxies, measure the size and age of the observable universe, probe far enough back in time to capture galaxies soon after their formation, and provide crucial keys to the evolution of chemical elements within stars.

All of these predicted advances have been realized, but the list of unforeseen Hubble accomplishments may prove even greater. Hubble did discover "adolescent" galaxies, but it also saw much farther back in time to capture galaxies on the very threshold of formation. Einstein's theory of general relativity was bolstered by the detection and measurement of myriad gravitational lenses, each one probing the mysterious dark matter that pervades galaxies and clusters of galaxies. Gamma-ray bursts had puzzled astronomers for more than 20 years; in concert with ground and X-ray telescopes, Hubble placed them near the edge of the visible universe and established them as the universe's brightest beacons, outshining whole galaxies for brief moments. Perhaps most spectacularly, Hubble confirmed and strengthened preliminary evidence from other telescopes for the existence of "dark energy," a new constituent of the universe that generates a repulsive gravity whose effect is to drive galaxies apart faster over time. The resulting acceleration of universal expansion is a new development in physics, possibly as important as the landmark discoveries of quantum mechanics and general relativity near the beginning of the 20th century.

Closer to home, Hubble has zeroed in on our own cosmic past by uncovering virtual carbon copies of how the Sun and solar system formed. Dozens of protoplanetary disks have been found encircling young stars in nearby star-forming regions of the Milky Way. The sizes and densities of these disks show how surplus dust and gas collect near infant stars to form the raw material of planets. Dozens of large, Jupiter-like planets have been discovered, initially by other telescopes but recently by Hubble using a new and more precise method. Measuring the tiny drop in light as a planet transits the disk of its parent star, the new technique could lead to a method for discovering Earth-like planets—a discovery with tremendous long-term implications for the human race.

I would like to stress that results from Hubble **–** its pictures and the new concepts that have flowed from these images – have captured the imagination of the general public, not only in our country but around the world. Hubble has been one of the most important outreach instruments in terms of its contributions to public awareness of science and of the universe in which we live.

Fascinating as they are, the scientific returns (and the public interest and excitement) from Hubble are far from their natural end. With its present instruments the telescope could continue probing star formation and evolution, gathering more data on other planetary systems, revealing phenomena of the planets and comets in our own solar system, and exploring the nature of the universe at much earlier times**.**

Two new instruments, already built for NASA's previously planned servicing mission (SM-4), would amplify the telescope's capabilities by allowing qualitatively new observations in two underexploited spectral regions. Such rejuvenation via new instruments has occurred after every Hubble servicing mission, and the next one promises to be no different. Wide Field Camera-3 (WFC3) would increase Hubble's discovery efficiency for ultraviolet and near-infrared imaging by factors of 10 to 30. The UV channel coupled with the camera's wide field of view will image the final assembly of galaxies still taking place in the universe. The near-infrared channel of WFC3 favors discovery of the very youngest galaxies, whose light is maximally red-shifted. The available UV, visible, and near-IR channels will combine to give a sweeping, panchromatic view of objects as diverse as star clusters, interstellar gas clouds, galaxies, and planets in our own solar system.

The second new instrument, the Cosmic Origins Spectrograph (COS), will increase Hubble's observing speed for typical medium-resolution ultraviolet spectroscopy by at least a factor of 10 to 30, and in some cases by nearly two orders of magnitude. Ultraviolet spectra carry vital clues to the nature of both the oldest and the youngest stars, yet UV rays are totally invisible to ground-based telescopes. COS will fill important gaps in our understanding of the birth and death of stars in nearby galaxies. Even more impressive, COS will use the light of distant quasars to spotlight previously undetectable clouds of dispersed gas between nearby galaxies, thereby mapping in unprecedented detail the properties of the so-called "cosmic web."

The future accomplishments I have described, and the many unforeseen discoveries that are impossible to predict but certain to occur, are what would be lost if Hubble was not serviced or replaced. It might be argued, of course, that the universe will be here into the future for other space missions to explore further. However, a number of NASA space astronomy missions presently in flight as well as planned, including the X-ray satellite Chandra and the infra-red satellite Spitzer, would not be as productive as they can be if synergistic data from Hubble were not to be available for analyses. The most recent Decadal Survey of Astronomy has predicated its recommendations for the future of the research field, and for the future facilities that would be needed for future advances, on the existence of Hubble data and its use in conjunction with other NASA space astronomy missions. My colleague Professor Joseph Taylor, a Co-Chair of this Decadal Survey, is here today and can address this aspect of Hubble much better than can I.

It is important to recognize that a central issue in the discussions that entered into our committee's conclusions is that the Hubble has a limited life; it was designed from the outset to be serviced periodically. A lengthy delay in servicing (the technical details are described in detail in our report) could result in a permanent loss of the telescope and even in a telescope orientation that would prevent ultimate safe de-orbit.

As shown in our report, it is most likely that an interruption of science operations will occur due to gyroscope failure some time in mid- 2007 unless servicing occurs. The ultimate, irreversible, failure of the telescope in the next several years is dependent on battery lifetime. Our committee spent a great deal of time investigating the conditions of the batteries (with a sub group of the committee speaking to NASA and other engineers, including the battery manufacturer, and studying data from battery life tests in a laboratory) and concluded that the window for battery failure that would end science operations opens in about May 2007. The window for potential vehicle failure opens in 2009. While there are many considerations in coming to these dates, there are few options beyond servicing for improving the outcome. The batteries themselves are not greatly affected by lighter loading that might be possible by early termination of science operations since operations will already be terminated at an early date due to loss of gyros.

Comparison of Robotic Servicing, Shuttle Servicing and Rehosting

Let us leave aside for the moment the issue of placing the Hubble instruments on some other spacecraft and begin with the realization that, given the predicted failure of the on-board gyros, HST most likely will need to terminate science operations by mid-2007. Based on this engineering determination which we believe to be correct, any servicing mission, shuttle or robotic, must be accomplished by the end of 2007 at the latest to prevent an interruption in science. A delay past 2007 not only results in increasing odds that the repair mission will meet an impaired Hubble when it launches. In the case of a robotic mission, it also means a growing reduction in the remaining lifespan of the serviced Hubble because, unlike a human servicing mission, it will be incapable of correcting most types of avionics system failures. A 2009 robotic mission would occur at a time when the telescope is already at the fifty percent risk point.

Even NASA's most optimistic projections places the robotic mission in December 2007, and this estimate was made when the NASA project hoped to receive full funding for development in both 2005 and 2006, something that has not occurred. Because the impact of reduced funding is always schedule delay, and often increased risk, there is a low probability of being able to undertake a successful robotic mission in time to save HST, even if much of the hardware has already been assembled and all of the systems testing had been successfully accomplished.

Now, let us compare a robotic servicing mission with a shuttle servicing one. Some of the important strengths of a shuttle servicing mission are (1) it has been done successfully before – four times in fact – so there is no new development required; (2) all of the instruments and replacement equipment have been built or can be made ready, so there is low schedule risk; (3) numerous life extension upgrades that are not feasible on a robotics mission could be carried out; (4) the shuttle has a proven capability for repairing Hubble with one hundred percent success history from four missions; and (5) a human mission has the unique ability to respond to last-minute requirements, usually driven by unforeseen failure (such as the need for new magnetometer covers that occurred on SM-1). In addition, and very importantly, the SM-4 mission could reduce the risk and cost of the eventual de-orbit mission for Hubble by pre-positioning a docking mechanism and associated fiducials on the aft end of the telescope so that the rendezvous and docking of the de-orbit module would be greatly facilitated over the uncooperative target that the telescope presently offers to any robot approaching it. The main weaknesses in a shuttle servicing mission are that the schedule depends on successful shuttle Return To Flight (RTF), and there is a small crew safety risk by flying one shuttle mission in addition to the 25 to 30 that are estimated by NASA as required for completion of the ISS. The additional shuttle mission would also delay ISS assembly by 3 to 5 months, thereby increasing slightly shuttle program costs (in comparison to total shuttle program costs) at the end of the shuttle life, currently projected for 2010.

The strengths of a robotic mission are (1) it avoids the risks to astronauts of one additional shuttle flight; (2) it is exciting technology; and (3) some of the technology may have applications to other space activities. The weaknesses are primarily those associated with successfully achieving an extremely ambitious mission on an aggressive schedule, and the risk to HST (not only to HST science but also to eventual successful de-orbit) of using it as a target vehicle for the demonstration of unproven technology. It also has very large costs, both near and far term costs; an estimate of $2.2 billion (or more including launch costs) was provided to NASA by the Aerospace Corporation. Those members of the committee who are familiar with such costs believe that this number is plausible.

From the risk mitigation viewpoint, the committee stated in our report that the planned use for the robotic servicing mission of the mature ISS robotic arm and robotic operational ground system helps reduce both the schedule risk and the development risk for this mission. However, the committee found many other serious challenges to the development of a successful robotic mission. Some of these challenges are due to the simple fact that Hubble was not designed to be serviced robotically, and thus has hardware features that are designed for human, not robot, interactions. Challenging issues for a successful robotic mission include:

- Technologies required for close proximity operations and autonomous rendezvous and capture of the telescope have not been demonstrated in a space environment.

- The control algorithms and software for several proposed systems such as the laser ranging instrument (lidar) and the camera-based control of the grapple arm are mission-critical technologies that have not been flight-tested.

- Technologies needed for autonomous manipulation, disassembly and assembly, and for control of manipulators based on vision and force feedback have not been demonstrated in space.

- The Goddard HST project has a long history of Hubble shuttle servicing experience, but little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the proposed HST robotic servicing mission.

- The Committee found that the Goddard HST project had made advances since January 2004. However, the Committee also found that there remain significant technology challenges and – very significantly – major systems engineering and development challenges to successfully extend the lifetime of HST through robotic servicing.

- The proposed Hubble robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The committee concluded that the likelihood of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

Rehosting

Rehosting of the two new instruments COS and WFC3 was the final option I was asked to discuss in my testimony today. In theory, the flight of these existing instruments on a new astronomy mission would be a possible means of obtaining some of the science that would otherwise be lost if Hubble were not repaired through a shuttle servicing mission. The information that was provided by NASA to the committee on possible re-hosting options was very sketchy, certainly not as defined and as detailed as was much of the technical information available for servicing Hubble. One clear advantage of any re-host mission is that it would use a spacecraft that employed current era technologies. Possible re-hosting missions could be to either a low Earth orbit (LEO), such as the one that Hubble is currently flying in, or to some other orbit, such as geosynchronous or a Lagrangian point. It was unclear to the committee which, if any, of these orbits was under any serious consideration by NASA. Thus, I have to speculate somewhat as to what might be being proposed today, some four months after the committee's last meeting.

A re-host mission to geosynchronous orbit or to a Lagrangian point would require the employment of launch vehicles that would permit the mission to arrive at, and to survive there. A spacecraft to a Lagrangian point location would likely involve a thermal design that was simpler than is used on Hubble since no eclipses would occur in that orbit. At geosynchronous orbit, eclipses occur twice a year, such as geosynchronous communications spacecraft experience. The relative absence of eclipses at geosynchronous or at a Lagrangian point would also allow a higher duty cycle for the acquisition of science data. Any new telescope located at either location would not be practical to service, a feature that has allowed the HST to be continually upgraded since launch.

Independent of the lack of solid technical (to say nothing of lack of schedule) information on re-host options, the committee had a number of important concerns with respect to the practical aspects of rehosting. In order to obtain science returns from the COS and the WFC3 comparable to the return from the instruments if they were flown on Hubble, the new satellite would have to carry a 2.4 meter diameter mirror, with diffraction-limited performance down to the ultraviolet (such a mirror diameter is especially necessary for the science of the WFC3 instrument), together with a very accurate pointing and guiding system that would be consistent with HST's capabilities. The two instruments would also have to be modified from their present states in order to be able to effectively use the new un-aberrated mirror that would likely be designed and built for the new spacecraft. (It seems inconceivable to me that an aberrated mirror would be purposefully designed for a brand new spacecraft just to match the Hubble's aberrated mirror.) In essence then, NASA would need to commit to, and to build and fly, a new Hubble telescope with an unaberrated mirror. The original Hubble development and testing program involved a lengthy and costly process. For mission success, this new re-host development program would require a commitment of very significant resources as well as political support over an interval of several years. The committee questioned whether such a commitment is likely to be given, let alone sustained in the face of numerous competing, high-priority, peer-reviewed astronomy programs that are already planned.

Even if the new Hubble program were adequately supported, such a program would come with the added risks that technical problems could halt or seriously delay development. In addition, as already noted in the Aerospace Corporation report, it was not clear to the committee that there would be significant cost savings over the options for a shuttle SM4 repair mission, particularly given the uncertainties of developing an entirely new satellite that performs like the original Hubble. Finally, unlike a Hubble repair, a satellite with re-hosted instruments would represent a significant new astronomy program that never was carefully evaluated for cost and schedule in the deliberative, detailed planning process that was carried out for astronomy research in the most recent Decadal Survey —a process that involved a great many resource and schedule trade-offs.

The SM4 Hubble service mission has been in NASA plans and budgeting profiles for years. In contrast, it would appear that any consideration of any re-hosting option would need to obtain and to critically evaluate accurate data on the costs for a satellite development mission of a complexity almost identical to that for the original Hubble. In addition, the review of a re-hosting mission by the astronomy community would have to establish its relative priority for funding and scheduling in terms of planned and on-going programs.

For these reasons, I personally would have strong reservations regarding a plan to re-host the COS and the WFC3 Hubble instruments on another satellite, particularly when compared to a shuttle repair mission. If a shuttle repair mission were not possible—if for instance NASA was not successful in returning shuttle to flight—then I would argue that the trade-offs of performing a re-hosting mission should be reviewed by the astronomy community in the context of its overall planning for space astronomy in the next decade.

In conclusion, I would like to reiterate the committee's conclusions that Hubble is a scientific asset of extraordinary value to the nation, and that shuttle servicing is the best option for extending the life of Hubble.

Thank you for the opportunity to appear before you today. I am prepared to answer any questions that you may have.